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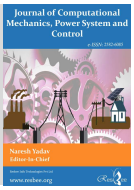

Optimized Fractional-Order PID Control for Robust MPPT in PV Systems

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Abstract: Photovoltaic (PV) energy is a crucial component of the shift to renewable power infrastructure, based on the necessity for effective power conversion and a decrease in reliance on fossil fuels. The key to maximizing photovoltaic system performance is MPPT, which makes sure that the maximum amount of solar energy is captured even in the face of changing climatic conditions. Among various MPPT strategies, optimization-based controllers have gained increasing attention due to their ability to enhance convergence speed and reduce steady-state oscillations. This paper proposed an Optimized Fractional-Order Proportional Integral Derivative (FOPID) Control approach for Robust MPPT in PV Systems. The PV energy conversion system integrated with an optimized FOPID MPPT controller. The PV module converts solar energy into electrical power producing a voltage that varies with solar irradiance and temperature. The controller adaptively responds to irradiance variations ranging from 650 to 1000 W/m² over 0.5 s, ensuring stable and efficient operation. Comparative analyses among PID, FOPID, PI and optimized FOPID controllers show that the proposed optimized FOPID approach provides faster convergence, higher tracking precision and improved robustness. The optimized FOPID delivers the best accuracy and stability, achieving the lowest minimum error of 0.0193, maximum error of 14.158, average error of 5.4219 and standard deviation of 3.1254. These performance metrics demonstrate consistent superiority across both transient and steady-state operating conditions. The result confirms that the optimized FOPID enhances MPPT efficiency and overall PV system reliability, offering a promising solution for solar energy applications.

Keywords: Photovoltaic, Fractional Order Proportional Integral Derivative, Proportional Integral, Maximum Power Point Tracking, Proportional Integral Derivative

Nomenclature

Abbreviation	Description
PV	Photovoltaic
P-V	Power-Voltage
FOPID	Fractional Order Proportional Integral Derivative
MPPT	Maximum Power Point Tracking
OCV	Open Circuit Voltage
MPP	Maximum Power Point
FOCV	Fractional Open Circuit Voltage
MCA	Musical Chairs Algorithm
AVO-RNN	African Vulture Optimized Recurrent Neural Network
SAPF	Shunt Active Power Filter
AVO	African Vulture Optimization
AVSS	Adaptive Variable Step Size
EMRAC	Enhanced Model Reference Adaptive Controller
NNE	Neural Network Estimator
P&O	Perturb and Observe
FOCV	Fractional Open Circuit Voltage
MCA	Musical Chairs Algorithm

1. Introduction

Photovoltaic (PV) energy is advanced in being sustainable, clean and abundant. It is a extremely promising to traditional fossil fuel-based energy generation. As the world continues to move towards more eco-friendly energy sources, these features make PV a compelling option [1]. In recent years, photovoltaic systems have also become central to global energy transition strategies due to their scalability and minimal environmental impact. Towards the worldwide movement decarburization and decentralized power

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generation, increasing the need for sustainable [2]. Due to the supportive policies, declining costs and technological advancements, the worldwide solar energy deployment has grown quickly [3]. PV systems hold significant potential to address the energy access issues in Africa, where solar irradiance is among the greatest in the world, particularly in isolated and underserved areas [4]. However, environmental oscillations including temperature changes, partial shadowing and variations in irradiance can impair the performance and dependability of PV installations the performance and reliability of PV installations [5]. These variations introduce nonlinearities and uncertainties that complicate accurate power extraction from PV arrays.

Variable climatic conditions can still affect photovoltaic systems, which have enhancements in the power output and efficiency, by fluctuating atmospheric conditions, resulting in suboptimal performance, the PV systems can still be impacted [6]. These variations create nonlinear operating characteristics that make accurate power extraction challenging under real-world conditions. To overcome these issues, the Maximum Power Point Tracking (MPPT) system has become a critical element [7]. The Maximum Power Point (MPP) denotes the point of maximum power output on the solar panel's Power-Voltage (P-V) curve is dynamically tracked by the MPPT technology [8]. Accurate tracking of this point ensures maximum energy harvesting efficiency regardless of load and weather variations. The MPPT system ensures more consistent and reliable power generation even in the face of shifting atmospheric circumstances by continuously adjusting and monitoring the operating point to maintain this MPP [9][10]. Under both uniform and varying weather conditions, PV installations are designed to deliver optimal performance and maximize power generation [11][12].

By continuously aligning the panels with the position of the sun, Solar tracking mechanisms are essential for increasing the energy yield of PV systems [13]. These tracking systems significantly improve energy capture efficiency compared to fixed-tilt PV installations. The modular structure of the Solar PV systems allows their deployment across a wide range of applications, from large-scale power plants to small household installations [14]. This flexibility supports widespread adoption in both urban and rural energy infrastructures. Therefore, it is expected that the modules will become significantly cheaper due to competitive efforts to lower the costs of Solar PV [15][16][17] systems and an increase in the number of global Solar PV modules.

In this model, a robust MPPT strategy for PV systems is proposed to maximize energy extraction under varying irradiance and temperature while ensuring stability and efficiency [18][19]. Intelligent control strategies are increasingly being explored to overcome the limitations of conventional MPPT techniques under dynamic environmental conditions. An optimized FOPID controller enhances dynamic response, minimizes steady-state oscillations and adapts to environmental variations [20]. Fractional-order controllers offer improved flexibility and robustness compared to classical integer-order control systems. The paper proposes a FOPID-based MPPT controller for photovoltaic systems to improve maximum power extraction under varying irradiance conditions. The PV system is integrated with the optimized FOPID controller to ensure efficient energy conversion through adaptive tracking of the maximum power point. The novelty of the proposed work is the optimization of FOPID parameters, which enhances robustness, reduces tracking error, and improves convergence speed under dynamic environmental changes.

The paper is structured as follows: Section 2 reviews existing literature on MPPT control techniques for stand-alone photovoltaic systems. Section 3 outlines the design and formulation of the proposed optimized FOPID control approach. Section 4 describes the experimental setup and evaluates the results obtained. Section 5 summarizes the main conclusions and highlights directions for future research.

2. Literature Review

2.1. Related Work

In 2021, AS Saidi et al [21] proposed an advanced approach for executing the Maximum Power Point Tracking (MPPT) system for the PV panel. The proposed approach focused on improving the precision of voltage estimation under varying environmental conditions. The system consists of an optimal duty cycle calculation stage, a conversion coefficient and a Neural Network Estimator (NNE). For different temperature values, the suggested NNE technique, determines the ratio of the OCV at each level of solar irradiance to the corresponding standard OCV. Artificial intelligence-based estimators have become increasingly popular for MPPT applications due to their adaptive learning capabilities. For each solar radiation, a regularization coefficient was calculated that uses the OCV to predict the voltage that corresponds to the maximum power.

In 2024, C Jiang [22] suggested an African Vulture Optimized Recurrent Neural Network (AVO-RNN) approach to eliminate the extreme power of the presented solar vitality for a three-phase Shunt Active Power Filter (SAPF) grid-linked PV structure. Hybrid optimization algorithms combined with neural

networks can significantly improve tracking efficiency under fluctuating irradiance conditions. A hybrid approach was suggested to improve MPP tracking in solar panels. By combining both the voltage and current outputs of the PV array, with the duty cycle of the DC-DC boost converter serving as the output constraint, it addresses the drawbacks of traditional approaches under varying irradiation The recommended approaches were reduced an AVOA-RNN-based MPPT controller derived from the AVO technique, which is employed to train the developed RNN by tuning its connection weights and biases. The optimization process enables improved convergence characteristics and enhances system adaptability during rapid atmospheric changes. This process enables the determination of an optimal duty cycle for the converter, ensuring operation of the PV array at its MPP.

In 2025, H Alhusseini et al [23] proposed an APSO-MPC MPPT algorithm. Metaheuristic optimization combined with predictive control has shown promising capability in handling nonlinear PV system behavior. It can rapidly track the maximum power using a minimal number of sensors, while maintaining low steady-state oscillations and avoiding deviation from the optimal power point under changing irradiance conditions. Moreover, by employing Adaptive Variable Step Size (AVSS), the proposed approach may eliminate trips between the GMPP and LMPP and monitor the GMPP in real time. The integration of adaptive step-size strategies further improves tracking accuracy and minimizes unnecessary oscillations around the operating point. The outcomes demonstrate the proposed approach could follow the ability to avoid local maximum traps, achieve faster convergence, fewer steady-state oscillations and the MPP with quicker convergence.

In 2024, S Manna et al [24] suggested a new hybrid two-stage MPPT system established to optimize efficiency and power extraction in PV systems. Hybrid MPPT methods are increasingly preferred because they combine the strengths of multiple control techniques to achieve better dynamic performance. The system was divided into two stages: the first stage employs EMRAC to regulate the duty cycle of the DC–DC converter, while the second stage utilizes a P&O-based MPPT to control the reference voltage. This configuration is primarily developed for a 100.7 kW three-phase grid-connected PV system operating under rapidly varying temperature and solar irradiance conditions. The proposed framework demonstrated enhanced adaptability under both sudden irradiance fluctuations and varying temperature conditions. Three uncertain conditions, including step irradiance profile, rapidly changing both temperature and irradiation profile and ropp.

In 2025, MJ Alshareef [25] introduced a hybrid MPPT method that combines the Fractional Open Circuit Voltage (FOCV) and Musical Chairs Algorithm (MCA). Optimization-based MPPT techniques continue to attract attention because of their capability to improve convergence speed and tracking efficiency. This method simplifies, reduces and processes the time needed to achieve optimal performance by using one decision variable. The new method provides better results than FOCV's power output and tracking efficiency. Using MATLAB/SIMULINK, the efficacy of this technique was evaluated under irradiance conditions such as real irradiance profiles, sinusoidal patterns and gradual changes. Simulation-based validation confirmed the suitability of the proposed method for practical PV applications under dynamic environmental conditions.

2.2 Problem Statements

The benefits and drawbacks of several current filtration approaches utilized for the MPPT control of stand-alone PV systems are discussed in the Table 1. A detailed comparative evaluation of existing MPPT methods is necessary to identify limitations affecting tracking stability and implementation efficiency. Paper [21] suggested an NNE approach that achieved accurate voltage prediction and high MPPT accuracy under varying temperature and solar radiation conditions, however, it required extensive training data and involved higher computational complexity. Paper [22] introduced an AVO-RNN method that enhanced MPPT performance under changing irradiation by integrating current, voltage and duty-cycle inputs for improved convergence and it also demanded higher complexity and increased training effort. Similarly, Paper [23] used an APSO-MPC method that ensured fast real-time tracking with fewer sensors, minimal steady-state oscillations and avoidance of local MPP traps. However, it required proper tuning and had significant complexity. Paper [24] proposed an EMRAC with P&O, achieving fast tracking, high efficiency and low power loss even under rapidly changing weather conditions, although this hybrid system increased complexity and required specialized hardware. Finally, Paper [25] suggested an FOCV + MCA technique that offered faster tracking, simplified decision variables and improved efficiency, although it struggled under irradiance variations and featured relatively high complexity.

The above literature review highlights several drawbacks including high computational complexity, difficult parameter tuning and increased hardware requirements. Many conventional and intelligent MPPT approaches also experience performance degradation under rapidly varying climatic conditions and partial shading effects. Most existing methods focus mainly on tracking accuracy while neglecting robustness, stability and cost-effective implementation. Therefore, this paper proposes an FOPID

controller for robust MPPT in PV systems designed to ensure stable and efficient energy extraction. The suggested optimized FOPID controller demonstrates superior dynamic performance compared with conventional PID, PI and standard FOPID controllers achieve faster convergence, higher tracking precision and enhanced robustness against irradiance variations. The comparative analysis confirms that the optimized FOPID provides the best accuracy and stability, attaining the lowest minimum error, reduced maximum error, lower average error and smaller standard deviation thereby significantly improving MPPT efficiency and overall PV system reliability.

Table 1. *Benefits and drawbacks of several current filtration methods used for the MPPT control of stand-alone PV systems*

Author	Methodology	Advantages	Disadvantages
AS Saidi et al [21]	NNE	Accurate voltage prediction for maximum power under varying temperature, solar radiation conditions and High accuracy	Requires training data, training quality affects performance and higher complexity.
C Jiang [22]	AVO-RNN	Enhanced MPP tracking under varying irradiation, better control performance by combining current, voltage, duty cycle and improved convergence	Higher complexity and increased training effort
H Alhusseini et al [23]	APSO-MPC	Fast tracking, reduced sensors, minimal steady-state oscillations, avoids local MPP traps and real time tracking	Complexity, requires proper tuning for stability and performance
S Manna et al [24]	EMRAC + P&O	Fast MPP tracking, high efficiency, low power loss and works well in rapidly changing weather.	Higher complexity due to hybrid system and Requires hardware platform
MJ Alshareef [25]	FOCV + MCA	Faster tracking, simplified decision variable and improved efficiency	Irradiance changes and high complexity

3. Proposed Methodology

3.1 PV energy system with optimized FOPID MPPT controller

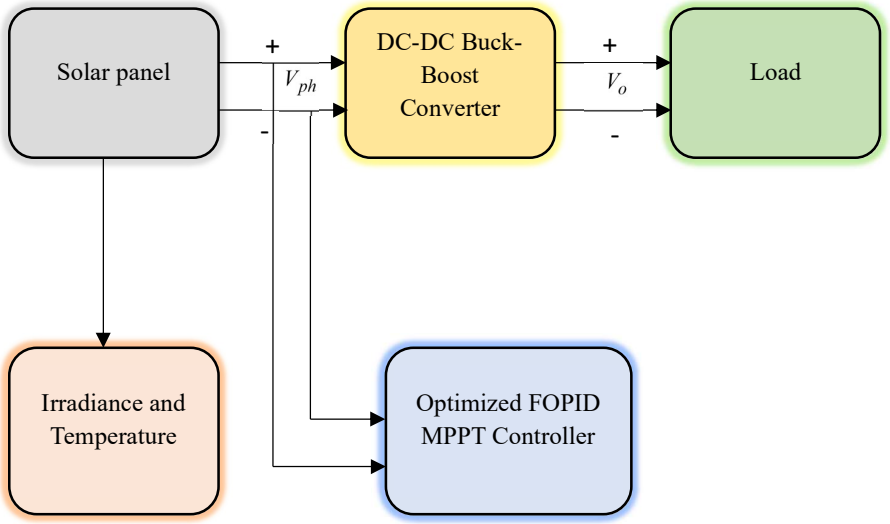

Fig. 1. *PV energy system with optimized FOPID MPPT controller*

Fig. 1 illustrates a PV energy conversion system integrated with an optimized FOPID MPPT controller. The proposed configuration is designed to maximize energy extraction efficiency under dynamically changing environmental conditions. The solar pannel converts solar energy into electrical power, producing a voltage V_{ph} that varies with solar irradiance and temperature. These environmental factors are continuously monitored and supplied to the FOPID MPPT controller, which processes the data along with the PV voltage to determine the optimal operating point for maximum power extraction. The controller regulates the duty cycle of the DC–DC boost converter, increasing the output voltage of the solar panel to match the requirements of the connected load. The optimized controller continuously adapts the converter operation to maintain stable system performance and minimize power losses. By continuously adjusting the converter in response to real-time operating conditions, the optimized FOPID-based MPPT controller

enables efficient performance of the solar system under varying environmental conditions. The boost converter delivers a stable and enhanced output voltage V_o to the load, maximizing the system performance and energy utilization of the solar power system.

3.2. Modeling of PV

The electrical equivalent of a PV cell consists of a current source placed in parallel with a diode. This equivalent circuit model is commonly used to analyze the nonlinear current-voltage characteristics of photovoltaic cells.The voltage and current relationship for the single-diode representation is expressed as follows

$$I = I_{ph} - I_S\left[\exp\left(\frac{q(V+IR_S)}{kTA}\right)-1\right]-\frac{V+IR_S}{R_{sh}} \tag{1}$$

Where, I represented the current, I_{ph} denotes the phase current, I_S is the series current, V represented the voltage, T illustrates the cell temperature, R_S is the series resistance and R_{sh} illustrates the shunt resistance. The photo generated current I_{ph} is determined is expressed as

$$I_{ph} = \frac{G}{G_{ref}}\left[I_{ph,ref} + C_T\left(T - T_r\right)\right] \tag{2}$$

Where, T illustrates the temperature of the cell in Kelvin and insulation is represented as G. The photocurrent increases proportionally with solar irradiance and is slightly affected by temperature variations. I_{rs} the PV cell's reverse saturation current, which varies with the temperature of cell, T is given by the following expression

$$I_s = I_{s,ref}\left[\frac{T}{T_{ref}}\right]^3 \exp\left(\frac{qE_G}{kA}\left[\frac{1}{T_{ref}}-\frac{1}{T}\right]\right) \tag{3}$$

Solar cells are interconnected in either parallel or series configurations to form an array. Series and parallel combinations are utilized to achieve the desired voltage and current ratings of the PV system. To ensure uniform performance, the cells within the array are matched to have identical characteristics. The PV array of the current-voltage relationship is expressed as

$$I = N_p I_{ph} - N_P I_s\left[\exp\left(\frac{q\left(V+IR_s\right)}{kTA}\right)-1\right]-\frac{V+IR_s}{R_{sh}} \tag{4}$$

3.3. Modeling of MPPT

This device is functional as a photovoltaic array boost converter. Due to the variations in temperature and irradiance, the output of the photovoltaic array differs throughout the period. Consequently, efficient MPPT techniques are essential to continuously extract the maximum available power from the PV array. As a result, increasing the photovoltaic output power was necessary. At the end, the incremental conductance method is chosen due to its fast response and enhanced MPPT performance under varying temperature and irradiance conditions, compared to other available techniques. In this approach, the MPP is reached when the derivative of power with respect to voltage becomes zero, indicating no change in power with voltage.

$$P_{pv.out} = V_{pv.out} * I_{pv.out} \tag{5}$$

$$\partial P_{pv.out} \Big/ \partial V_{pv.out} = I_{pv.out} * \partial V_{pv.out} \Big/ \partial V_{pv.out} + V_{pv.out} * \partial I_{pv.out} \Big/ \partial V_{pv.out} \tag{6}$$

$$\partial I_{pv.out} \Big/ \partial V_{pv.out} = -I_{pv.out} \Big/ V_{pv.out} \tag{7}$$

The calculation of MPP is shown in equations (5)-(7). Where output of PV power is represented as $P_{pv.out}$. voltage variation, current variation and Power variation are represented as $\partial V_{pv.out}$, $\partial I_{pv.out}$ and $\partial P_{pv.out}$. The incremental conductance algorithm compares incremental conductance with instantaneous conductance to accurately determine the operating point relative to the MPP.

3.4. Modeling of a FOPID Controller

To get most of the PV system in all weather conditions, a closed-loop FOPID controller tracks the data V_{ref} produced by the FNN block. Fractional-order control techniques provide enhanced flexibility and robustness compared to conventional PID controllers. Fractional-order operators are added to an integer-

order PID controller to create the FOPID control process. The linear combination of the systems is the derivative of error, the integral of error and classical error is the formulation of the FOPID control law. The derivative control factor decreases the steady-state oscillations and the integral control factor decreases the instantaneous error while following the reference trajectory. The formulation of the FOPID voltage regulator is expressed below.

$$d(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d e(t) \tag{8}$$

The converter's output $e(t) = V_{ref} - V_0(t).e(t)$ denotes the error between the actual and the reference voltage. k_d denotes the differential gain, k_p represents the proportional constant and k_i denotes the integral constant. The additional fractional orders improve the controller's capability to handle nonlinear and uncertain system dynamics.

The value of d(t) is scaled to lie within the range of 0 to 1, to the IGBT switches under every operating condition are bounded between 0 and 100%.

Where, Q^{λ} is denoted as the fractional order operators, λ denotes the magnitude of the fractional order. The fractional operator is symbolically denoted by Q

$$Q^{\lambda} f(t) = \frac{1}{\Gamma(n-\lambda)} \frac{d^m}{dt^m} \int_a^t \frac{f(\tau)}{(t-\tau)^{\lambda-m+1}} d\tau \tag{9}$$

Where the Euler gamma function is symbolically represented as $\Gamma(x)$, m denotes the integer such that $m-1 < \lambda < m$.

$$Q^{\lambda} f(t) = \lim_{h \to 0} \frac{1}{h^i} \sum_{i=0}^{(t-a)/h} (-1)^i \binom{\lambda}{i} f(t-ih) \tag{10}$$

Where $\binom{\lambda}{i} = \Gamma(\lambda+1) / \Gamma(i+1)\Gamma(\lambda-i+1)$ and step size is denoted as h.

$$Q^{\lambda} f(t) = \frac{1}{\Gamma(\lambda-m)} \int_a^t \frac{f^m(\tau)}{(t-\tau)^{\lambda-m+1}} d\tau \tag{11}$$

Thus, the FOPID controller is expressed by substituting the differential operators and conventional integer-order integral with their fractional order equivalents expressed below

$$d(t) = k_p e(t) + k_i \left(Q^{-\alpha} e(t) \right) + k_d \left(Q^{\gamma} e(t) \right) \tag{12}$$

The parameters γ and α represent the fractional order associated with the differential and integral operators, both constrained within the interval [0,1].In this formulation, the standard integer-order integral operator is substituted by $Q^{\gamma} e(t)$, whereas the integer-order integral operator is replaced by $Q^{-\alpha} e(t)$. With these additions, the conventional PID controller is extended to include five tunable parameters, $(k_d, k_p, k_i, \gamma and \alpha)$ are increases the flexibility to efficiently regulate the control signal and system state deviations. The corresponding transfer function of the FOPID controller is given below

$$C(s) = \frac{D(s)}{E(s)} = k_p + \frac{k_i}{s^{\alpha}} + k_d s^{\gamma} \tag{13}$$

Here s denotes the Laplace operator. Due to the fractional nature of the terms s^{α} and s^{γ} their computational implementation becomes considerably challenging.

$$s^{\lambda} = \prod_{i=1}^{p} \frac{1 + \left(\frac{s}{\upsilon_{z,i}} \right)}{1 + \left(\frac{s}{\upsilon_{p,i}} \right)} \tag{14}$$

Such that $\upsilon_{z,i} = \upsilon_L \left(\frac{\upsilon_H}{\upsilon_L} \right)^{\frac{2i-1-\lambda}{2M}}$ and $\upsilon_{p,i} = \upsilon_L \left(\frac{\upsilon_H}{\upsilon_L} \right)^{\frac{2i-1+\lambda}{2M}}$. Here p denotes the order of the filter, whereas υ_H and υ_L represented the upper and lower frequencies. A 5th-order Oustaloup's filter is suggested with $\upsilon_H = 10^2$ and $\upsilon_L = 10^{-3} rad/s$ to estimate the fractional operators. The robustness and stability of the proposed FOPID controller are then evaluated using standard frequency-domain measures, namely the gain margin and phase margin.

3.5 Modelling of DC-DC Buck Boost converter

The operation of a buck-boost converter [26] can be categorized into two modes: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). The converter enables both voltage step-up and voltage step-down operations depending on the duty cycle. A critical inductance value L_C is shown in equation (15), determines the mode of operation. When the inductance L is lower than this critical value L_C, the buck-boost converter operates in DCM.

$$L_C = (1-\alpha)^2 RT \tag{15}$$

The switching cycles represents by T .Equation 16 determined the output voltage. This relationship indicates that the voltage output may be either less than or greater than the input voltage, depending on the duty cycle. When the duty cycle is below 0.5, the voltage output is lower than the input. In contrast, when it is above 0.5, the output voltage exceeds the voltage input.

$$V_o = \frac{\alpha}{1-\alpha} V_i \tag{16}$$

Where α represents the duty cycle and V_i represents the input volage. The voltage ripple is given as equation (17)

$$\frac{\Delta V_o}{V_o} = \frac{\alpha T}{CR} \tag{17}$$

In every switching period the operation of a buck-boost converter in CCM is divided into two stages. During mode 1, the Q transistor is turn on and VD diode is reversed biased.

When a buck-boost converter works in CCM, its behavior within each switching cycle can be divided into two distinct modes. During Mode 1, the diode transistor Q is turn on and VD is reversed biased. allowing the input current to flow through the circuit. During this interval, energy is stored in the magnetic field of the inductor.

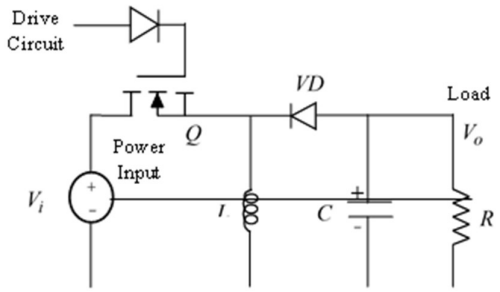

Fig. 2. *Buck-Boost Converter Topology*

The input current flow into transistor Q and inductor L. The Inductor L will store energy and the inductor current will raise. Simultaneously, capacitor C provides energy to the load R. During mode 2, the transistor Q is turned off, and the current flowing through the inductor (L) is redirected through the diode VD, capacitor C and load R. In this stage, the stored energy in the inductor is transferred to the output load and capacitor. Whereas, the inductor current gradually decreases until the transistor Q is switched on again.

4. Result and Discussion

To evaluate the performance of the optimized fractional-order PID control for robust MPPT in PV systems, MATLAB 2021 b and a corresponding Simulink model. The simulation framework was developed to analyze the dynamic performance of the proposed controller under varying irradiance and measurement noise conditions. This section presents a comparative analysis between the proposed optimized FOPID approach and three existing advanced control techniques. The results and discussion focus on system behavior under varying solar irradiance conditions, the overall performance of advanced PV controllers, and a comparison of MPPT methods based on error-related metrics.

The performance evaluation primarily considers tracking accuracy, convergence speed, stability, and robustness against environmental disturbances. Fig. 3 illustrates the irradiances over time. The horizontal axis represents time in seconds (0-0.5s), whereas the vertical axis shows irradiance in watts per square meter (w/m^2) extending from 600 to 1050. primarily, the irradiance remains constant at 650 (w/m^2) up to 0.1s, then it increases from 650 to 850 (w/m^2) up to 0.25s. Again, it increases from 850 to 950 (w/m^2) up

to 0.4s. Lastly the step increases and reaches 1000 (w/m^2). The blue line shows the stepwise increments in irradiance occurring at specific time intervals.

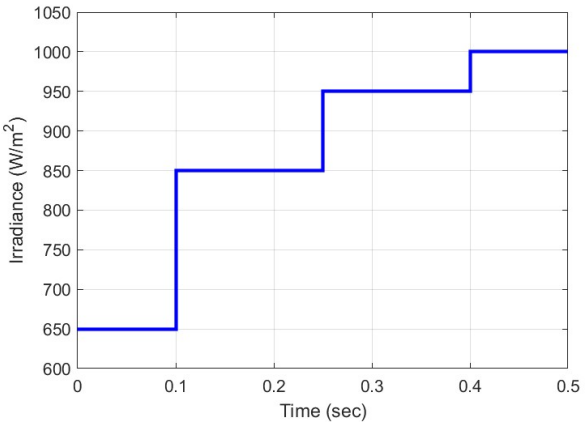

Fig. 3. *Dynamic changes in solar irradiances*

The varying irradiance profile is used to validate the adaptability and robustness of the MPPT controllers under rapidly changing atmospheric conditions. Fig. 4 shows the power response of various controllers, namely PID, PI, FOPID and optimized FOPID, compared to time. The plot shows the time duration from 0 to 0.5s, whereas the power varies within the range from 280 to 480W.In the analysis, the proposed optimized FOPID-based stand-alone PV systems achieved a value of 292. 6614W. However, the existing methods, such as PID, PI and FOPID, attained the value of 310.0702W, 310.0702W, 310.0702W, respectively and also, they achieve the power reference of 292.5W at time t = 0.008s. The optimized FOPID controller demonstrates improved transient response with reduced oscillations and enhanced stability under 10 dB measurement noise.

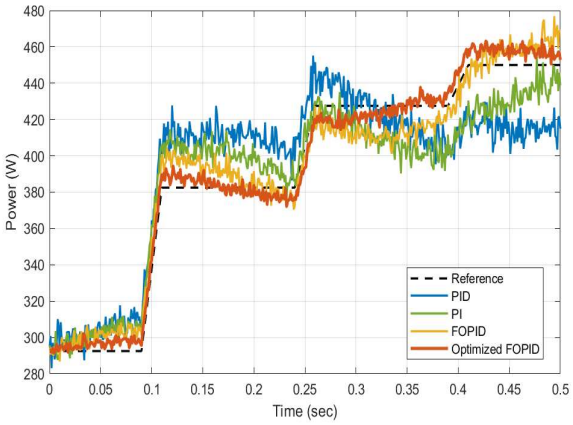

Fig. 4. *Power response comparison under measurement noise 10 dB*

Fig. 5 illustrates the power response of various controllers, namely PID, PI, FOPID and optimized FOPID, compared to time. The plot shows the time duration from 0 to 0.5s, whereas the power varies within the range from 340 to 480W. In the analysis, the proposed optimized FOPID-based stand-alone PV systems achieved a value of 335.2327951W. However, the existing methods such as PID, PI and FOPID attained the value of 348.162465W, 351.308346W, 341.436443W, respectively and also, they achieve the power reference of 328.5W at time t = 0.098s. The results indicate that the optimized FOPID controller maintains superior tracking capability and reduced steady-state fluctuations even as measurement noise increases to 20 dB.

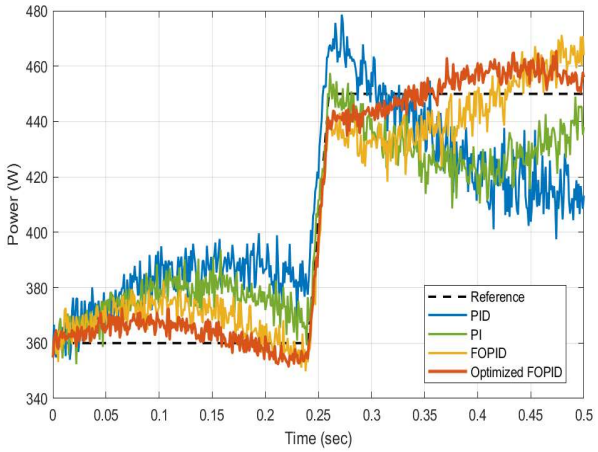

Fig. 5. *Power response comparison under measurement noise 20 dB*

Fig. 6 shows the power response of various controllers, namely PI, PID, FOPID and optimized FOPID, compared to time. The graph shows the time duration from 0 to 0.5s, whereas the power varies within the range from 280 to 480W. In the analysis, the proposed optimized FOPID-based stand-alone PV systems achieved a value of 380.6053282W. However, the existing methods such as PID, PI and FOPID attained the value of 409.370371W, 394.306217W, 390.245208W, respectively and also they achieve the power reference of 382.5W at time t = 0.198s. The optimized FOPID controller exhibits enhanced robustness against severe noise disturbances, maintaining faster convergence and lower power oscillations compared to conventional approaches.

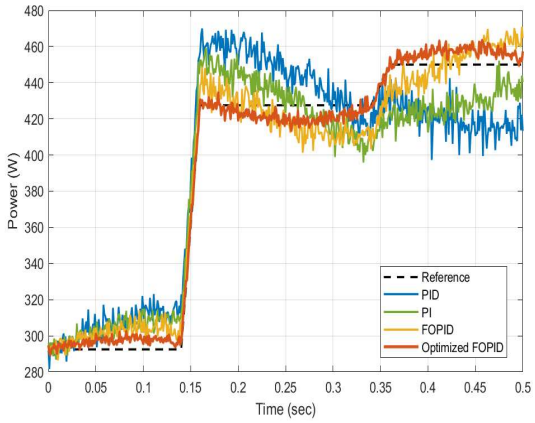

Fig. 6. *Power response comparison under measurement noise 30 dB*

Table 2. *Comparison of MPPT Controllers Based on Error Metrics*

S. No	Method	Min Error	Max Error	Avg Error	Std Deviation
1	PID	0.2055	48.913	21.188	11.157
2	PI	0.1402	38.091	15.879	8.6341
3	FOPID	0.0263	26.939	9.7525	5.6571
4	Optimized FOPID	0.0193	14.158	5.4219	3.1254

Table 2 quantitatively validates the superiority of the optimized FOPID controller in terms of accuracy, consistency, and robustness under varying operating conditions. The comparison of control methods in Table 2 shows that the optimized FOPID controller provides the best performance. The PID controller results in the highest average error of 21.188 and standard deviation of 11. 157. Similarly, the PI controller with an average error of 15.879 and a standard deviation of 8.6341. The FOPID controller significantly improves performance, reducing the average error of 9.7525 and the standard deviation of 5.6571. The optimized FOPID delivers the best accuracy and stability, achieving the lowest minimum error of 0.0193, maximum error of 14.158, average error of 5.4219 and standard deviation of 3.1254.

5. Conclusion

In this study, the proposed optimized FOPID-based MPPT controller for PV systems evaluate and analysis were carried out to validate its performance under real-time dynamic conditions. The proposed control strategy demonstrated effective tracking capability and enhanced robustness under varying environmental conditions. The proposed approach effectively adapts to rapid changes in solar irradiance ensuring stable operation and improved energy extraction efficiency. The PV module converts solar energy into electrical power producing a voltage that varies with solar irradiance and temperature. The integration of the optimized FOPID controller with the PV system significantly improved the dynamic response and reduced steady-state oscillations during operation. During the assessment, the controller adaptively responds to irradiance changes between 650 W/m² and 1000 W/m² within 0.5 s, ensuring stable energy extraction and maintaining system efficiency despite environmental fluctuations. The adaptive optimized FOPID achieved a minimum error of 0.0193, maximum error of 14.158, an average error of 5.4219and a standard deviation of 3.1254, outperforming conventional PID, PI and standard FOPID controllers. The simulation outcomes confirm that the optimized FOPID controller provides faster convergence speed, improved tracking precision and better robustness against irradiance variations compared to existing approaches. From the results, it was proven that the optimized FOPID-based MPPT attains superior accuracy, robustness and convergence speed. However, real-world PV variations and computational complexity may affect scalability and real-time implementation. The implementation of fractional-order controllers in practical systems may require advanced digital processors and efficient optimization algorithms to reduce computational burden. Future work can focus on enhancing adaptability, computational efficiency and exploring hardware-based real-time MPPT applications using advanced optimization strategies.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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